

WISE J080822.18–644357.3 – a 45 Myr-old accreting M dwarf hosting a pre-transitional disc

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ABSTRACT

WISE J080822.18–644357.3 (WISE J0808–6443) was recently identified as a new M dwarf debris disc system and a candidate member of the 45 Myr-old Carina association. Given that the strength of its infrared excess ($L_{\text{IR}}/L_{\star} \approx 0.1$) appears to be more consistent with a young protoplanetary disc, we present the first optical spectra of the star and reassess its evolutionary and membership status. We find WISE J0808–6443 to be a Li-rich M5 star with strong H α emission ($-125 < \text{EW} < -65 \text{ \AA}$ over 4 epochs) whose strength and broad width are consistent with accretion at a low level ($\sim 10^{-10} M_{\odot} \text{ yr}^{-1}$) from its disc. The spectral energy distribution of the star is consistent with a two-temperature disc structure, with a hot inner disc ($T_{\text{in}} \approx 1100 \text{ K}$) at orbital radius $\sim 0.006 \text{ au}$ and a warm outer disc ($T_{\text{out}} \approx 230 \text{ K}$) at radius $\sim 0.12 \text{ au}$. The dust belts likely correspond to the sublimation temperatures of silicates and icy planetesimals, respectively. We calculate an improved proper motion based on archival astrometry, and combined with a new radial velocity, the kinematics of the star are consistent with membership in Carina at a kinematic distance of $90 \pm 9 \text{ pc}$. The spectroscopic and photometric data are consistent with WISE J0808–6443 being a $\sim 0.1 M_{\odot}$ Classical T-Tauri star and one of the oldest known accreting M-type stars. These results suggest that the upper limit on the lifetimes of gas-rich discs around the lowest mass stars may be longer than previously recognised, or some mechanism may be responsible for regenerating short-lived discs at later stages of pre-main sequence evolution. Low-level accretion for tens of Myr may provide a mechanism for the migration, eccentricity dampening, and resonance locking of small planets, like those recently reported for the TRAPPIST-1 exoplanetary system.

Key words: stars: kinematics and dynamics – stars: pre-main-sequence – stars: fundamental parameters – solar neighbourhood – open clusters and associations: individual: Carina

1 INTRODUCTION

Through the work of the NASA *Disk Detective* citizen science project¹ (described in Kuchner et al. 2016), Silverberg et al. (2016) recently identified WISE J080822.18–644357.3 (hereafter WISE J0808–6443) as a new M dwarf debris disc candidate exhibiting significant excess emission in the 12 and $22 \mu\text{m}$ bands of the *Widefield Infrared Survey Explorer* (WISE) survey (Wright et al. 2010). Adopting the proper motion provided by the Southern Proper Motion Catalog (SPM4; Girard et al. 2011), Silverberg et al. used the Bayesian Analysis for Nearby Young AssociationNs II tool (BANYAN II; Malo et al. 2013; Gagné et al. 2014) to establish whether the star was associated with any of the seven nearest young moving groups in the Solar neighbourhood (see reviews by Zuckerman & Song 2004; Torres et al. 2008; Mamajek 2016), finding a 93.9 per cent probability that it is a member of the 45 Myr-old Carina association at a distance of $\sim 65 \text{ pc}$. If confirmed, this would make WISE J0808–6443 the oldest known M dwarf debris disc within 100 pc and therefore represent a benchmark object with

which to study late-stage disc evolution in low-mass stars. Despite the proper motion match to Carina, Silverberg et al. presented no spectroscopic evidence for either youth or group membership. In this work we test their claims by analysing new optical spectra of WISE J0808–6443 (Section 2), deriving a revised proper motion for the star from archival astrometry (Section 3) and reanalysing its spectral energy distribution and infrared excess (Section 4). With this new information we re-evaluate the evolutionary state of the star-disc system and discuss its origins with regards to the dozen or so known young moving groups near the Sun.

2 SPECTROSCOPIC OBSERVATIONS

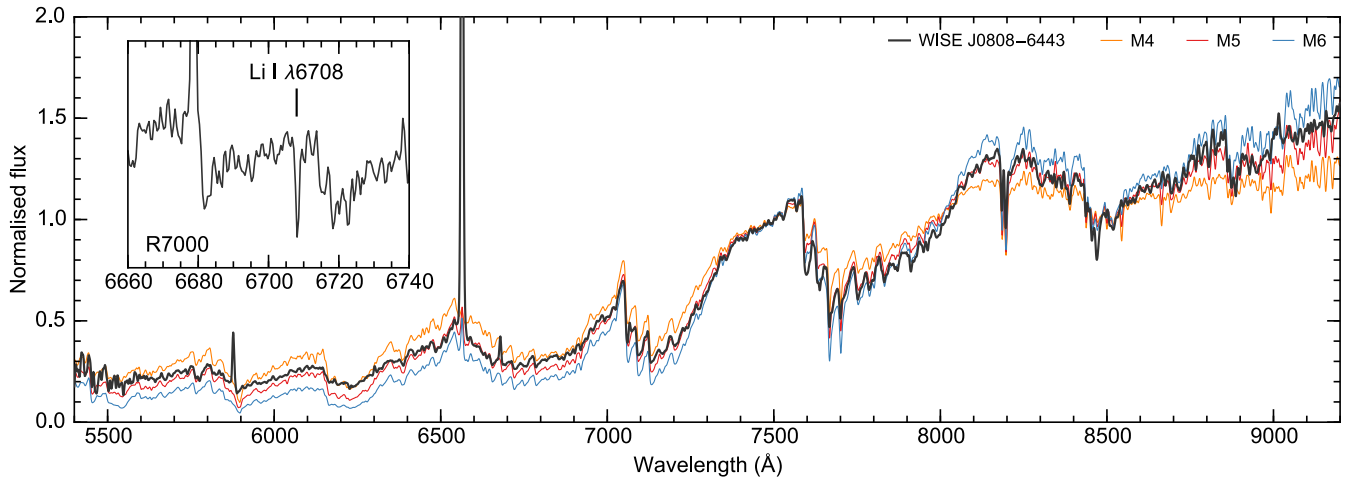
We acquired four spectra of WISE J0808–6443 during 2017 January and February using the Wide Field Spectrograph (WiFeS; Dopita et al. 2007) on the ANU 2.3-m telescope at Siding Spring Observatory. The R7000 grating gives a resolution of $R \approx 7000$ over a wavelength range of $5250\text{--}7000 \text{ \AA}$, while the R3000 grating covers $5400\text{--}9700 \text{ \AA}$ at a resolution of $R \approx 3000$. Details of the instrument setup and reduction process, including the measurement of radial velocities, are provided in Murphy & Lawson (2015) and

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¹ <http://www.diskdetective.org>

Table 1. Summary of ANU 2.3-m/WiFeS observations of WISE J080822.18–644357.3.

UT Date	Grating /Dichroic	Spectral Type	RV (km s ⁻¹)	EW[Li I] (mÅ)	EW[H α] (± 5 Å)	v_{10} [H α] (± 10 km s ⁻¹)	EW[He I λ 5876] (Å)	EW[He I λ 6678] (Å)
2017 Jan 7	R7000/RT480	M4 (veiled?) ^a	25.7 \pm 1.9 ^d	300 \pm 50	-110	352	-7.5	-2.7
2017 Jan 9	R7000/RT480	M4.5 ^a	22.3 \pm 1.6 ^d	400 \pm 30	-125	332	-5.3	-1.8
2017 Feb 6	R7000/RT480	M4.5 ^a	22.5 \pm 0.5 ^d	390 \pm 30	-65	298	-6.4	-1.5
2017 Feb 6	R3000/RT560	M5 ^b , M4.8 \pm 0.2 ^c	-75	419	-7.5	-3.3

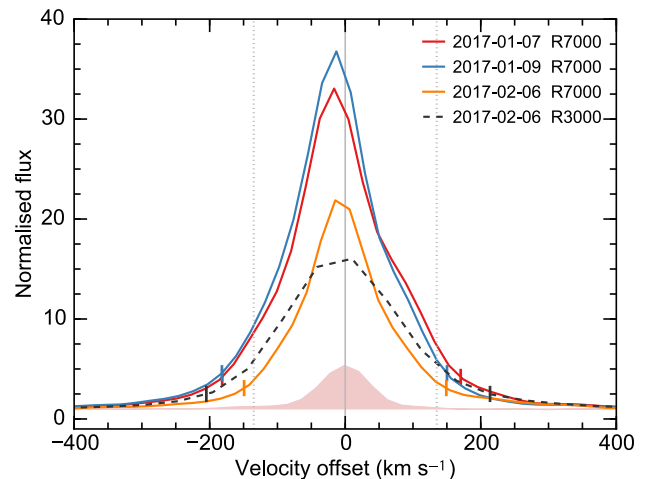
^a Based on comparison to SDSS M dwarf templates over 5300–7000 Å.^b Based on comparison to SDSS M dwarf templates over 5500–9200 Å.^c Average of R1, R2, R3, TiO8465, c81 and VO2 molecular indices, as calibrated by [Riddick et al. \(2007\)](#).^d Mean and standard deviation of velocities calculated from 14 (January) and 4 (February) M-type standards.**Figure 1.** Telluric-corrected WiFeS/R3000 spectrum of WISE J0808–6443 compared to the SDSS average M dwarf templates of [Bochanski et al. \(2007\)](#). Both the WiFeS and SDSS spectra were Gaussian-smoothed and normalised at 7500 Å prior to plotting. Strong H α , He I λ 5876 and λ 6678 emission is apparent, as well as prominent Na I absorption at 8200 Å. On this scale the H α line continues to a peak flux of 4.85 (see also Fig. 2). The inset shows the region around the Li I λ 6708 youth indicator in the higher-resolution 2017 February 6 WiFeS/R7000 spectrum. Note also the strong He I λ 6678 emission.

[Bell, Murphy & Mamajek \(2017\)](#). The results of these observations are given in Table 1 and the R3000 spectrum is shown in Fig. 1.

WISE J0808–6443 is clearly of mid-M spectral type, with pronounced H α and He I emission. We also detected strong Li I λ 6708 absorption in the R7000 spectra and weak (~ 1 Å) forbidden [O I] λ 6300 emission in all four observations. We measured the equivalent width (EW) of the broad H α line by direct integration of the line profile. After comparing the R3000 spectrum to the SDSS average M dwarf templates of [Bochanski et al. \(2007\)](#), we estimate a spectral type of approximately M5, in agreement with the M4.8 \pm 0.2 average of the R1, R2, R3, TiO8465, c81 and VO2 molecular indices (covering 7800–8500 Å), as calibrated by [Riddick, Roche & Lucas \(2007\)](#). From the three R7000 spectra we calculate a weighted mean radial velocity of 22.7 ± 0.5 km s⁻¹ and EW[Li I] = 380 ± 20 mÅ. The smaller EW[Li] on 2017 January 7 may be evidence of veiling. Within the limits of the modest WiFeS resolution, the radial velocity appears constant on timescales of ~ 1 month and the star’s cross correlation function is consistent with a slowly-rotating ($v \sin i \lesssim 45$ km s⁻¹) single star (see discussion in [Murphy & Lawson 2015](#)).

2.1 H α emission and accretion

Accretion of gas-rich material from the inner regions of a circumstellar disc onto the star is typically accompanied by enhanced Balmer and other line emission (e.g. [Muzerolle, Hartmann & Calvet 1998](#)). The H α emission observed in WISE J0808–6443 (see Fig. 2) is much larger than typically seen in mid-M field stars and immediately suggests the star is accreting. [White & Basri \(2003\)](#)

**Figure 2.** WiFeS H α velocity profiles of WISE J0808–6443. All spectra have been shifted to the heliocentric rest frame. Vertical markers show the velocities at which the flux is 10 per cent of the peak value. The two dotted lines are the (symmetric) $v_{10} = 270$ km s⁻¹ accretion criterion of [White & Basri \(2003\)](#). For comparison, the shaded region shows the H α profile of the new M5 TW Hydrae association member and non-accretor TWA 36 (EW = -9.5 Å, $v_{10} = 169$ km s⁻¹; [Murphy et al. 2015](#)).

and [Barrado y Navascués & Martín \(2003\)](#) found that mid-M stars with EW[H α] < -20 Å tend to be T-Tauri stars with other corroborating evidence of accretion (strong IR excess, veiling). Simi-

larly, by comparing the *Spitzer* infrared colours of young stars with and without dusty inner discs, Fang et al. (2009) proposed an EW limit of -18 \AA for an M5 accretor. Over three nights we measured EW[H α] values in the range $-125 < \text{EW} < -65 \text{ \AA}$, considerably in excess of these criteria (see Fig. 3). We note, however, that for a fixed accretion luminosity, the EWs observed in WISE J0808–6443 should be larger than in younger stars, whose brighter continua will reduce the contrast of the H α emission.

The width of the H α line (typically quantified by the velocity full width at 10 per cent of peak flux, or v_{10}) is also used to distinguish accretors from stars whose narrower emission is due to chromospheric activity. White & Basri (2003) proposed a limit of $v_{10} > 270 \text{ km s}^{-1}$ for accretors independent of spectral type, while Jayawardhana, Mohanty & Basri (2003) and Fang et al. (2013) have suggested limits of 200 km s^{-1} and 250 km s^{-1} , respectively. Fig. 2 shows the H α line profiles of our four WiFeS spectra. We calculated v_{10} values by fitting a linear function over $\pm 500\text{--}1000 \text{ km s}^{-1}$ and normalising the spectra, then determining the two velocities at which the flux profile fell to one tenth of its peak value (see Fig. 2). These v_{10} measurements are given in Table 1 and Fig. 3, and are clearly indicative of accretion.

The variability of the EW and v_{10} values in Table 1 is commonly seen in other accretors (e.g. Nguyen et al. 2009; Costigan et al. 2012) and probably indicates variability in the accretion rate. Applying the $v_{10}[\text{H}\alpha]$ – \dot{M}_{acc} relation of Natta et al. (2004) to our R7000 spectra yields mass accretion rates of $(1.0\text{--}3.3) \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ ($-10 < \log \dot{M}_{\text{acc}}/M_{\odot} \text{ yr}^{-1} < -9.5$), with an uncertainty of 0.4 dex ($2.5 \times$)². These rates are comparable to those observed in low-mass members of the TW Hydrae association, η Cha cluster and Scorpius-Centaurus OB association (Muzerolle et al. 2000; Lawson, Lyo & Muzerolle 2004; Murphy, Lawson & Bento 2015) and are 1–2 orders of magnitude below those typically inferred in young star-forming regions such as Taurus and ρ Ophiuchus (e.g. Calvet, Hartmann & Strom 2000).

2.2 Lithium depletion and low-gravity features

Because lithium is easily destroyed in stellar interiors, with some caveats the presence of Li I $\lambda 6708$ absorption in a star is a sign of youth. As a co-eval group of young stars contracts toward the main-sequence, their core temperatures rise until at $\sim 3 \times 10^6 \text{ K}$ lithium burns. These temperatures can be reached in either fully convective mid- to late-M dwarfs or at the base of the convective zone in late-K/early-M dwarfs. Between these luminosities, rapid depletion ensues and the Li I $\lambda 6708$ feature is no longer visible. This mass-dependent behaviour leads to the depletion patterns seen in Fig. 4, where we plot the EW[Li I] of WISE J0808–6443 compared to young moving group members from the literature. Based on the moderate amount of depletion observed in the star, we can immediately infer that it is older than the $\sim 10 \text{ Myr}$ TW Hydrae association (TWA), whose mid-M members are essentially undepleted.

The Carina association is believed to be part of a larger complex (the so-called Great Austral Young Association or GAYA; Torres et al. 2001, 2008) comprising itself and the Columba and Tucana-Horologium associations. Although spatially and kinematically distinct, Bell, Mamajek & Naylor (2015) found that all three associations are co-eval, with ages of $\sim 45 \text{ Myr}$. Unlike Carina, which is a particularly sparse association of a few dozen high-probability members (see Section 3.1), Tuc-Hor contains hundreds

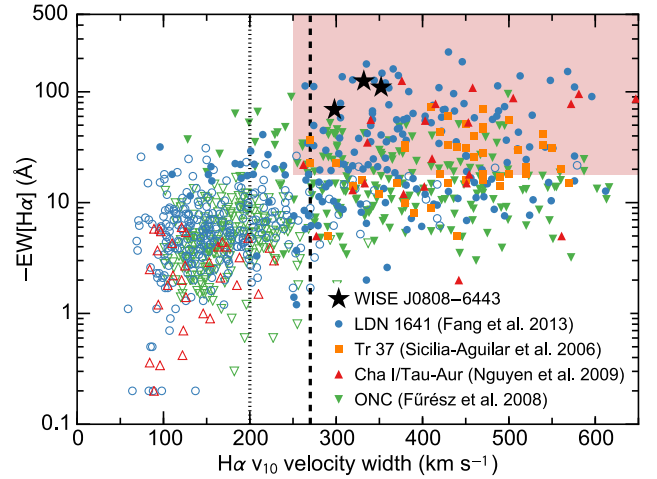


Figure 3. EW[H α] and $v_{10}[\text{H}\alpha]$ measurements for WISE J0808–6443 compared to members of young clusters and star-forming regions; LDN 1641 (Fang et al. 2013), Trumpler 37 (Sicilia-Aguilar et al. 2006), Cha I and Taurus-Auriga (Nguyen et al. 2009) and the Orion Nebula Cluster (Fűrész et al. 2008). Filled points are accretors with confirmed inner discs from *Spitzer*, open points are non-accretors. The dotted and dashed lines mark the v_{10} accretion criteria proposed by Jayawardhana et al. (2003) and White & Basri (2003), respectively, while the shaded region shows the criteria for an M5 accretor proposed by Fang et al. (2009, 2013).

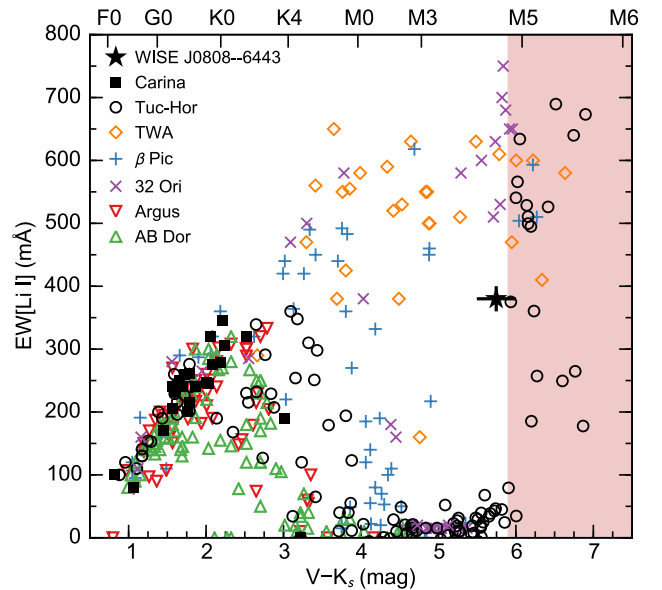


Figure 4. EW[Li I] of WISE J0808–6443 compared to other young moving group members, compiled from the studies of da Silva et al. (2009), Schneider et al. (2012), Kraus et al. (2014), Malo et al. (2014b), Binks & Jeffries (2016) and Bell et al. (2017). For WISE J0808–6443 we assume an uncertainty of 0.2 mag on its faint SPM4 V-band magnitude. The shaded region denotes the Li-rich side of the Tuc-Hor lithium depletion boundary.

of stars (Kraus et al. 2014). This census provides a well-sampled depletion pattern for stars at age $\sim 45 \text{ Myr}$ and we may use this to assess whether the Li depletion of WISE J0808–6443 is consistent with such an age. From Fig. 4 it is clear that WISE J0808–6443 occupies a region between the Li-poor early M-type Tuc-Hor members and the Li-rich mid to late M-type members. This sharp discontinuity (see the shaded region of Fig. 4) defines the lithium depletion boundary (LDB) of the association and its luminosity provides a precise, almost model-independent age of $40 \pm 3 \text{ Myr}$ (Kraus et al. 2014). The position of WISE J0808–6443 in Fig. 4 is entirely consistent with the expected LDB position for a co-eval population

² The Natta et al. relation was determined from a sample of few Myr-old stars and is not strictly applicable to older pre-MS stars, whose radii will be smaller and surface gravities higher. Assuming a constant accretion luminosity L_{acc} , the radius and hence mass accretion rate $\dot{M}_{\text{acc}} \propto L_{\text{acc}} R_{\star} / G M_{\star}$ onto a $0.1 M_{\odot}$ star is $\sim 4 \times$ (0.6 dex) smaller at an age of 40 Myr compared to 2 Myr (Feiden 2016).

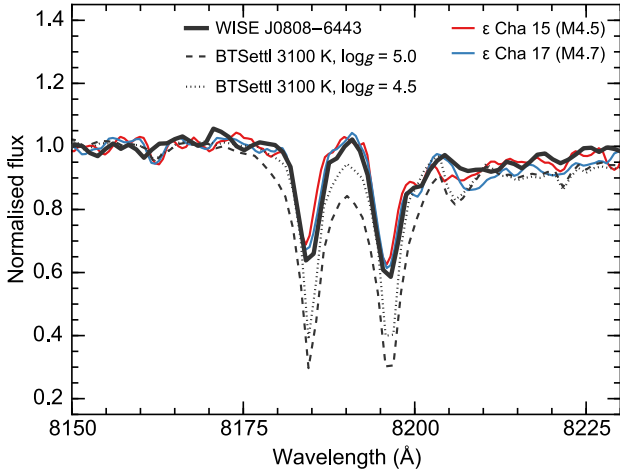


Figure 5. WiFeS/R3000 spectrum around the 8200 Å Na I doublet. The strength of Na I absorption is similar to members of the young ϵ Cha association (Murphy et al. 2013). Also plotted are two 3100 K BT-Settl model atmospheres (Baraffe et al. 2015), smoothed to $R \approx 3000$ and placed on the same wavelength scale as WISE J0808-6443. The absorption in WISE J0808-6443 is much weaker than the $\log g = 5.0$ model, particularly in the broad line wings, but similar to the $\log g = 4.5$ spectrum.

of nominal age 40–45 Myr. A strong upper age limit is provided by the 80–90 Myr LDB age of the α Persei cluster, whose LDB occurs at a spectral type of M6–6.5 (Stauffer et al. 1999; Barrado y Navascués, Stauffer & Jayawardhana 2004).

As the radius of a star decreases during its pre-main sequence (pre-MS) evolution, surface gravity-sensitive absorption features, such as those of the alkali metals or metal hydrides, can be used as indicators of a star’s youth. At mid-M spectral types, one of the best gravity-sensitive features is the Na I doublet at $\lambda 8183/8195$ (Schlieder et al. 2012). While the Na I line strength can not provide a precise estimate of age, it has been widely used to distinguish young cluster members from giants and Gyr-old field stars (e.g. Slesnick, Carpenter & Hillenbrand 2006). We plot in Fig. 5 the region around the Na I doublet for WISE J0808-6443 and two members of the 3–5 Myr-old ϵ Cha association of similar spectral type, observed with the same instrument settings (Murphy, Lawson & Bessell 2013). The strength of the absorption in WISE J0808-6443 ($\text{EW}[\text{Na I}] \approx 4 \text{ \AA}$) is very similar to the two young stars, and is much weaker than a dwarf model atmosphere of similar temperature. This shows that WISE J0808-6443 has a weaker surface gravity and hence younger age than a field M dwarf.

In light of its strong H α emission, lithium absorption and low gravity, we spectroscopically classify WISE J0808-6443 as an accreting, Classical T-Tauri Star (CTTS).

3 PROPER MOTION AND KINEMATICS

Silverberg et al. (2016) assigned WISE J0808-6443 as a candidate member of the Carina association based entirely on its position and SPM4 proper motion, considering no other astrometric catalogues. The SPM4 proper motion has large uncertainties ($\sim 7 \text{ mas yr}^{-1}$) and so a critical examination of other proper motion measurements and an independent estimate is warranted. Table 2 lists the published proper motions for WISE J0808-6443 and our new measurement (see below). It is apparent that the proper motion of the star is not well constrained, with large differences between catalogues (e.g. $\Delta\mu_\delta \approx 19 \text{ mas yr}^{-1}$ between SPM4 and PPMXL; Röser, Demleitner & Schilbach 2010). Furthermore, the USNO B1.0 catalogue (Monet et al. 2003) lists a proper motion of zero for this star, which signifies it was unable to detect a statistically significant proper mo-

Table 2. Estimated proper motions for WISE J080822.18-644357.3.

Reference	$\mu_\alpha \cos \delta$ (mas yr $^{-1}$)	μ_δ (mas yr $^{-1}$)
SuperCOSMOS (Hambly et al. 2001)	-6.8 ± 4.8	18.5 ± 4.9
USNO-B1.0 (Monet et al. 2003)	0 ± 0	0 ± 0
PPMXL (Röser et al. 2010)	-11.2 ± 8.5	17.8 ± 8.5
SPM4 ^a (Girard et al. 2011)	-9.9 ± 7.1	36.7 ± 7.1
AllWISE (Cutri et al. 2014)	53 ± 27	-14 ± 27
HSOY (Altmann et al. 2017)	-14.0 ± 3.1	27.9 ± 3.1
This work ^b	-12.5 ± 1.9	29.4 ± 2.2
This work (adopted) ^c	-12.5 ± 2.1	29.4 ± 2.5

^a Value adopted by Silverberg et al. (2016).

^b Based on a simple least-squares fit.

^c Calculated as in ^b, but multiplies the uncertainty by a ratio taking into account the χ^2 of the fit.

tion. Given the ambiguity with regards to its proper motion, to assign membership of WISE J0808-6443 – and by extension an age – on the basis of a single poorly-constrained observable is clearly insufficient.

We calculated a new proper motion for WISE J0808-6443 using the published positions compiled in Table 3 and the least-squares formulae of Teixeira et al. (2000). Given the heterogeneity of the source catalogues and heteroskedasticity of their uncertainties, we assessed the proper motion uncertainties by multiplying the least-squares estimates by their Birge ratios (Mohr & Taylor 2005), in effect forcing the reduced χ^2 of the linear astrometric fits to be ~ 1 . As seen in Table 2, the differences in proper motion uncertainties between the simple least squares estimates and the Birge ratio-adjusted estimates are negligible. We adopt the latter for the kinematic calculations described below. Our new proper motion agrees with SPM4 to within the latter’s larger uncertainties and is similar to values recently published in the HSOY catalogue (Altmann et al. 2017, see Table 2), which was formed by combining *Gaia* DR1 astrometry (Gaia Collaboration et al. 2016) with PPMXL.

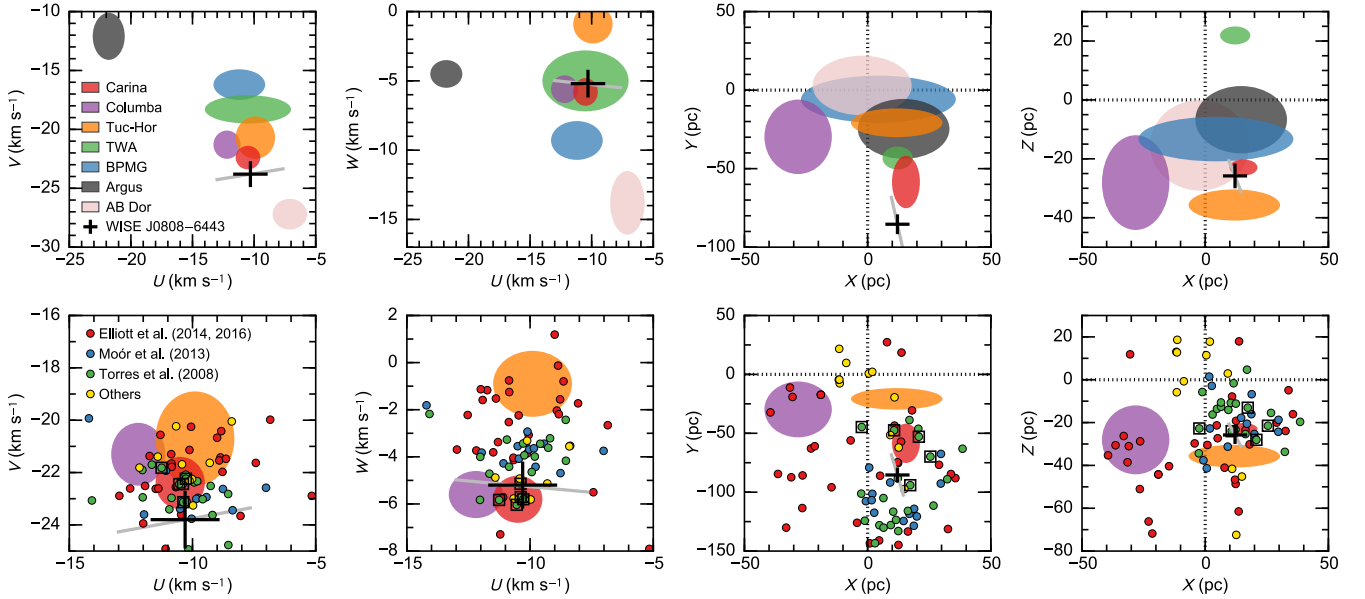
3.1 Young moving group membership

With our revised proper motion and radial velocity measurement we can better test the membership of WISE J0808-6443 in Carina or another of the young moving groups which populate the Solar neighbourhood. The BANYAN II Bayesian membership tool (v1.4) now returns a membership probability for Carina of 91.7 per cent (assuming $< 1 \text{ Gyr}$ age priors) at an inferred distance of $83 \pm 7 \text{ pc}$. This is comparable to the 93.9 per cent probability reported by Silverberg et al. at 65^{+9}_{-8} pc using the SPM4 proper motion. No other young group tested by BANYAN II (TW Hya, β Pic, Columba, Tuc-Hor, Argus, AB Dor) returned a non-zero membership probability, with the balance of probabilities going to the young field hypothesis. Several nearby, young moving groups are not included in BANYAN II – we additionally tested membership of WISE J0808-6443 in η and ϵ Cha (including ejection from η Cha; Murphy, Lawson & Bessell 2010), Octans and the Lower Cen-Cru subgroup of the Sco-Cen OB association, and could not find a satisfactory kinematic or spatial match (e.g. low membership probabilities, high peculiar motions, predicted radial velocities which disagree with measured value). WISE J0808-6443 is also in the vicinity of the IC 2602 and IC 2391 open clusters, but neither provide a plausible kinematic fit. Carina appears to be the only known group to which WISE J0808-6443 could plausibly belong.

Adopting the Malo et al. (2014a) mean space motion for Carina and our new proper motion for WISE J0808-6443, we use the convergent point method (e.g. Mamajek 2005) to calculate a kinematic parallax ($\varpi_{\text{kin}} = 11.16 \pm 1.13 \text{ mas}$; $d = 90 \pm 9 \text{ pc}$) and

Table 3. Astrometry used to calculate the proper motion of WISE J080822.18–644357.3.

α (deg.)	δ (deg.)	σ_α (mas)	σ_δ (mas)	Epoch (yr or JD)	Reference
122.0924291146	−64.7325757593	0.407	0.687	2015.0	<i>Gaia</i> DR1 (Gaia Collaboration et al. 2016)
122.0924381	−64.7326092	34	35.8	2010.5589	AllWISE (Cutri et al. 2014)
122.092536	−64.732738	400	400	2450916.764023	DENIS DR3 (Epchtein et al. 1999)
122.092519	−64.732778	400	400	2451237.607512	DENIS DR3 (Epchtein et al. 1999)
122.0925957	−64.7327013	69.5	69.5	2000.0	SPM4 (Girard et al. 2011)
122.092535	−64.732719	330	340	1991.131	GSC2.3.2 (Lasker et al. 2008)
122.092670	−64.732823	66	83	1985.1	USNO-B1.0 (Monet et al. 2003)

**Figure 6.** *Top row:* Three-dimensional Galactic velocity and position of WISE J0808–6443 relative to several nearby, young moving groups from Malo et al. (2014a). Uncertainties for WISE J0808–6443 were calculated from uncertainties on the proper motion, radial velocity and distance. The grey line shows the change in velocity and position as the 90 ± 9 pc assumed distance changes by $\pm 2\sigma$. Based on this comparison, WISE J0808–6443 is a likely Carina member. *Bottom row:* As above, but only showing the Carina, Columba and Tuc-Hor associations. Points are proposed Carina members from the literature with trigonometric parallaxes, predominantly from *Gaia* DR1. The five square markers are the ‘bona fide’ members of Malo et al. (2013, 2014a). These stars were the only Torres et al. (2008) members with *Hipparcos* parallaxes.

predicted radial velocity (21.5 ± 1.2 km s^{−1}). The larger distance stems from the revised proper motion having a smaller magnitude (32 mas yr^{−1}) than the SPM4 value (38 mas yr^{−1}). The star’s proper motion is pointing towards Carina’s convergent point, with only 2.4 ± 2.2 mas yr^{−1} of peculiar motion. We calculate a heliocentric position of $(X, Y, Z) = (12.1, -85.4, -25.8) \pm (4.9, 6.3, 4.2)$ pc and a space motion of $(U, V, W) = (-10.3, -23.8, -5.2) \pm (1.4, 1.1, 1.0)$ km s^{−1}, which agrees with the Malo et al. (2014a) mean group velocity at better than 2 km s^{−1}.

In the top row of Fig. 6 we plot the position and velocity of WISE J0808–6443 against the mean values for young moving groups and associations within 100 pc from Malo et al. (2014a). While there is excellent spatial and kinematic agreement between WISE J0808–6443 and Carina in this diagram, it is important to note that their Carina model is based on only five stars; AB Pic, HD 49855, HD 55279, V479 Car, and HD 83096AB, these being the only stars in the original membership list of Torres et al. (2008) with *Hipparcos* parallaxes. The updated models of Gagné et al. (2014) used by BANYAN II excluded V479 Car and added the nearby M dwarfs GJ 2079 and GJ 1167 (Shkolnik et al. 2012), but with only six systems the mean properties of Carina are poorly defined. We have gathered proposed Carina members from the literature with radial velocities and parallaxes (predominantly new measurements from *Gaia* DR1; Gaia Collaboration et al. 2016) and computed their space motions and positions which are plotted in

the bottom row of Fig. 6. These candidates came mainly from the memberships of Torres et al. (2008), Moór et al. (2013) and Elliott et al. (2014, 2016), with additional stars from Viana Almeida et al. (2009), Shkolnik et al. (2012), Riedel et al. (2014) and Bowler et al. (2015). Many of these stars have also been proposed as members of other young moving groups by various authors, especially Columba, with which Carina shares a similar position and velocity (see Fig. 6). For example, Elliott et al. (2014) reclassify seven Torres et al. (2008) members (including all five of the *Hipparcos* stars above) as either Columba members or Carina non-members, although their methodology or rationale is not given.

The general distribution of Carina candidates in Fig. 6 is spatially and kinematically distinct from both Columba and Tuc-Hor (whose mean phase space positions are much better defined from several tens of members with parallaxes). Carina is clearly much larger than defined by the five *Hipparcos* stars (which do not appear to be Columba members, c.f. Elliott et al. 2014), especially in the negative Y direction. This is similar to the solution proposed by Torres et al. (2008) with kinematic distances and is understandable as the limited depth of *Hipparcos* would favour nearby stars. Assuming they are all bona fide Carina members, from the 74 stars with parallaxes and radial velocities we calculate a mean space motion of $(-10.4, -22.2, -3.5) \pm (1.8, 1.4, 1.9)$ km s^{−1} (1σ variation), which is 2.3 km s^{−1} larger in W than the Malo et al. (2014a) veloc-

ity. If true, the revised space motion does not change our derived 90 pc kinematic distance by more than a parsec.

There are several proposed Carina members in the immediate vicinity of WISE J0808–6443. The Moór et al. (2013) star TYC 8933-1204-1 is only 1.40° away and, while it does not possess a *Gaia* DR1 parallax, its UCAC4 proper motion is only 5 mas yr^{-1} from that of WISE J0808–6443 and the stars’ radial velocities agree to 1 km s^{-1} . Of the proposed members with parallaxes, the G5 star TYC 8929-927-1 (Torres et al. 2008) is only 2.07° away, with radial velocity $23.4 \pm 0.5 \text{ km s}^{-1}$ (Torres et al. 2006) and $\varpi = 10.85 \pm 0.31 \text{ mas}$ ($d = 92.2 \pm 2.6 \text{ pc}$). The star’s *Gaia* proper motion matches that of WISE J0808–6443 to within $\sim 1 \text{ mas yr}^{-1}$. With a projected separation of $\sim 3.3 \text{ pc}$, it is unlikely that they are bound, but more likely unbound members of the same young moving group. Given their congruent proper motions, the *Gaia* parallax distance for TYC 8929-927-1 corroborates our kinematic distance of $90 \pm 9 \text{ pc}$ for WISE J0808–6443. Finally, we note that the Gagné et al. (2015) Carina candidate 2MASS J08045433–6346180 ($< M2$; 99 per cent BANYAN membership probability) is only 1.03° from WISE J0808–6443. Aside from being X-ray bright (1RXS J080455.0–634621), little is known about this star, though given its much larger UCAC4 proper motion it cannot be co-distant with WISE J0808–6443.

While a critical re-evaluation of all proposed Carina members in light of new *Gaia* parallaxes is beyond the scope of this work, given the close spatial and kinematic agreement between WISE J0808–6443 and the stars in Fig. 6, as well as the presence of other proposed Carina members in its vicinity, we see no reason not to assign membership to the association. Unambiguous confirmation, however, will require a refined Carina membership and a trigonometric parallax. *Gaia* should provide a parallax for a $G = 16 \text{ mag}$ M5 star with an estimated end-of-mission uncertainty of approximately $45 \mu\text{as}^3$.

4 CIRCUMSTELLAR DISC EMISSION

Silverberg et al. (2016) noted that WISE J0808–6443 has a strong infrared excess in the *WISE* W3 ($12 \mu\text{m}$) and W4 ($22 \mu\text{m}$) bands and fitted the star’s spectral energy distribution (SED) with a 2900 K stellar atmosphere and $\sim 260 \text{ K}$ blackbody of luminosity $L_{\text{IR}}/L_\star = 0.081$. In this section we re-examine the infrared excess using models and photometry provided by the Virtual Observatory SED Analyzer (VOSA v5.1; Bayo et al. 2008).

Within VOSA we first gathered all available photometry for WISE J0808–6443 from photometric catalogues. The resulting SED contained fluxes from *Gaia* DR1 (G), DENIS (iJK ; Epchtein et al. 1999), 2MASS (JHK_s ; Cutri et al. 2003) and AllWISE ($W1$ – $W4$; Cutri et al. 2014). Following Silverberg et al. we fit synthetic photometry derived from solar-metallicity BT-Settl models ($\Delta T_{\text{eff}} = 100 \text{ K}$; Baraffe et al. 2015), restricting the surface gravity to $\log g = 4.5$. The excess finding routine in VOSA identified a possible excess redward of $W1$ so in fitting the models we did not include the four *WISE* bands or the broad *Gaia* G -band, which may be contaminated by the accretion-driven strong $H\alpha$ line or any blue continuum excess⁴. For this reason we also excluded the SPM4 B - (photographic) and V -band photometry. Furthermore, we do not consider the effects of reddening in this analysis – at a kinematic distance of 80 – 90 pc , WISE J0808–6443 is expected to lie within

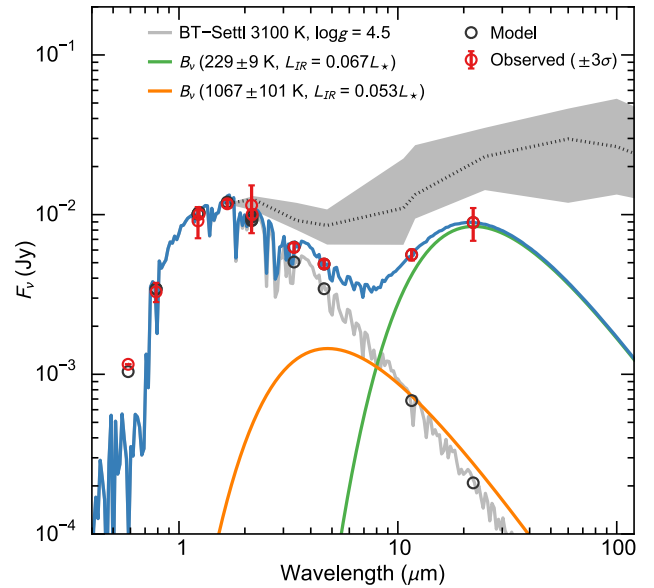


Figure 7. Spectral energy distribution of WISE J0808–6443, with photometry from *Gaia*, DENIS, 2MASS and *WISE* plotted in red with their 3σ uncertainties. The observed SED (blue line) is approximated by the sum of a 3100 K BT-Settl model and blackbodies of 229 K ($0.067 L_\star$) and 1067 K ($0.053 L_\star$), fit to the DENIS, 2MASS and *WISE* data. For comparison, the interquartile range of K5–M2 Class I Taurus sources from D’Alessio et al. (1999) is given by the shaded region, normalised at $1.6 \mu\text{m}$.

Table 4. Infrared excesses for WISE J080822.18–644357.3, assuming the intrinsic colours of a pre-MS M5 star from Pecaut & Mamajek (2013). Almost identical excesses are obtained using the main-sequence colours.

$E(K_s - W1)$ (mag)	$E(K_s - W2)$ (mag)	$E(K_s - W3)$ (mag)	$E(K_s - W4)$ (mag)
0.102 ± 0.034	0.267 ± 0.033	2.252 ± 0.039	4.017 ± 0.088

the Local Bubble and reddening maps predict its reddening and extinction should be negligible ($E(b-y) < 0.01$, $A_V < 0.04 \text{ mag}$; Reis et al. 2011).

The resulting SED and best-fit photosphere model of $T_{\text{eff}} = 3100 \text{ K}$ is shown in Fig. 7. This temperature is consistent with the WiFeS M5 spectral type and the corresponding dwarf temperature (3050 K) from Pecaut & Mamajek (2013). The SED T_{eff} is $\sim 200 \text{ K}$ hotter than the corresponding pre-MS temperature (2880 K) from the scale of Pecaut & Mamajek (2013), however their pre-MS sample of mid-M stars was dominated by younger, lower surface gravity stars from the ~ 10 – 25 Myr -old $\eta \text{ Cha}$, TW Hya, and $\beta \text{ Pic}$ groups. Combining these temperature estimates, we adopt $T_{\text{eff}} \approx 3050 \pm 100 \text{ K}$ for WISE J0808–6443.

From the SED fit it is clear that, in addition to the W3 and W4 bands, there are smaller excesses in both shorter wavelength *WISE* filters. This is also apparent when comparing the observed K_s –*WISE* colours to the intrinsic colours of an M5 star from Pecaut & Mamajek (2013, see Table 4). We attempted to fit a single blackbody to the infrared excess ($\sim 490 \text{ K}$; $L_{\text{IR}}/L_\star = 0.086$), but this gave a poor match to the $22 \mu\text{m}$ data. A double blackbody model with a ‘warm’ $\sim 230 \text{ K}$ outer component having $L_{\text{IR,warm}}/L_\star = 0.067$ and a ‘hot’ $\sim 1070 \text{ K}$ inner component with $L_{\text{IR,hot}}/L_\star = 0.053$ provides a good fit to the full gamut of *WISE* photometry (see Fig. 7). Together, the fractional luminosity of these components is $0.12 L_\star$ – 50 per cent brighter than the single temperature model of Silverberg et al. (2016).

Both the $W1$ and $W2$ photometry is listed in AllWISE as exhibiting strong variability (flag var = 9900). This is illustrated in

³ <http://www.cosmos.esa.int/web/gaia/science-performance>

⁴ By including the $W1$ magnitude in the VOSA BT-Settl model fit we were able to replicate the Silverberg et al. results and fit a 2900 K model atmosphere to the $(iJK)_{\text{DENIS}} JHK_s W1$ photometry. However, the χ^2 of this fit was much larger than the 3100 K fit obtained in this study.

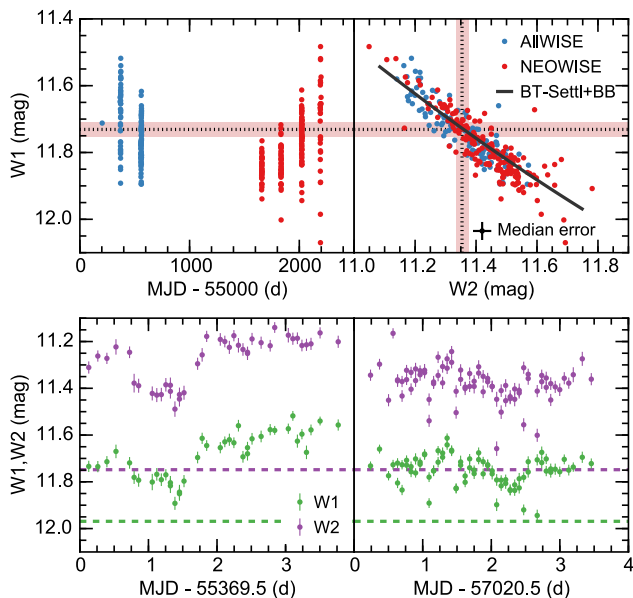


Figure 8. *Top left:* W1 individual epoch photometry for WISE J0808–6443 from both the AllWISE and reactivated NEOWISE (Mainzer et al. 2014) missions. *Top right:* Correlation of W1 and W2 magnitudes. The black line shows the expected relation for a 3100 K BT-Settl model combined with a 1067 K blackbody which varies in flux from zero to $0.11 L_{\star}$. The dotted lines in each panel are the mean AllWISE magnitudes used in the SED fit ($W1 = 11.731 \pm 0.022$ mag, $W2 = 11.354 \pm 0.020$ mag). *Bottom:* W1 and W2 time series for two four day windows in 2010 and 2014/15. The dashed lines are the photospheric contribution calculated from the BT Settl model and correspond to the faint end of the solid line in the upper right plot.

Fig. 8 where we plot ~ 300 individual epoch magnitudes for both the AllWISE and reactivated NEOWISE (Mainzer et al. 2014) missions. The variation in W1 and W2 is extremely well-correlated (Pearson $r \approx 0.9$) and much larger than both the typical uncertainties on a single measurement and the mean AllWISE photometry used in the SED fit. We could find no obvious periodicity in the time series, although the WISE sampling (few day observing blocks every six months) are not conducive to this. The smaller ($N \approx 40$) sample of W3 and W4 data show no such variability or correlation. Assuming it represents changes in circumstellar emission and not the photosphere, the short wavelength variability can be explained as the flux of the inner blackbody component changing with time from a negligible contribution to approximately $0.11 L_{\star}$ at fixed temperature (see Fig. 8), reflecting the amount of dust in the inner disc (c.f. $L_{\text{IR,hot}}/L_{\star} = 0.053$ for the mean SED fit in Fig. 7).

The SED of WISE J0808–6443 appears somewhat evolved compared to the median of K5–M2 Class I sources in Taurus reported by D’Alessio et al. (1999, grey shaded region in Fig. 7), with decreased flux across all WISE bands but retaining some excess flux in the near-infrared. We therefore classify the star as hosting a *pre-transitional* disc (Espanillat et al. 2012). These are usually modelled as an optically thick inner disc separated from an optically thick outer disc and suggest the development of inner gaps (perhaps due to orbiting planets) rather than the almost fully-cleared inner holes seen in true transition discs (Espanillat et al. 2007). Espanillat et al. (2012) find that the mass accretion rates in stars with pre-transitional and transition discs in Taurus, Chamaeleon, and NGC 2068 are lower on average than stars with full discs, though still an order of magnitude larger than we infer for WISE J0808–6443 (see Section 2.1). However, the relationship between accretion in young stars, their ages and the evolutionary state of their discs remains controversial (e.g. Fang et al. 2013).

Assuming large (blackbody) grains are responsible for the infrared excess, the blackbody temperatures correspond to emission

radii of $\sim 26 R_{\odot}^N$, (0.12 au) and $1.2 R_{\odot}^N$ (0.0057 au), respectively (Backman & Paresce 1993). The hot dust at the latter radius is likely associated with the gas feeding the accretion indicated by the H α and He I emission lines. We note that the temperature of the inner hot component is comparable to the temperatures where amorphous silicates anneal into crystalline form, before these sublimate at 1300–1400 K (Henning & Meeus 2009). Also, given the star’s size and approximate density ($\sim 5.6 \text{ g cm}^{-3}$), orbiting bodies with densities of $\sim 1\text{--}2 \text{ g cm}^{-3}$ would have Roche limits of $1.0\text{--}1.3 R_{\odot}^N$, indicating that the warm ($T \approx 1100 \text{ K}$) dust could be produced by disrupted planetesimals on trajectories taking them too close to the star (however this would not explain the accretion of gas onto the star). The cooler dust belt seems analogous to the ‘warm dust temperature’ debris discs with characteristic temperatures of $\sim 190 \text{ K}$ commonly seen among stars ranging from B- through K-type, and likely represents populations of small dust grains sublimating ice from icy planetesimals (Morales et al. 2011, 2016).

Integrating the BT-Settl model atmosphere to $1000 \mu\text{m}$ we find $\log(L/L_{\odot}^N) = -2.15 \pm 0.08$ dex at a distance of 90 ± 9 pc, in agreement with the $\log(L/L_{\odot}^N) = -2.17 \pm 0.10$ dex obtained using the 2MASS *J*-band magnitude and the relation between T_{eff} and the *J*-band bolometric correction given in Pecaut & Mamajek (2013)⁶. The estimated effective temperature ($3050 \pm 100 \text{ K}$) and bolometric luminosity of the star ($\log(L/L_{\odot}^N) = -2.15 \pm 0.08$ dex) are consistent with a stellar radius of $R_{\star} = 0.302 \pm 0.036 R_{\odot}^N$. In Fig. 9 we plot the Hertzsprung-Russell (H-R) diagram for WISE J0808–6443 along with the evolutionary tracks for solar metallicity stars from Baraffe et al. (2015) and the recent magnetic models of Feiden (2016) (also see Dotter et al. 2008). The latter were computed assuming the surface gas pressure is in equilibrium with the magnetic field pressure and adopt an equipartition magnetic field strength equal to the value at 50 Myr (typically a few kG). This is an approximation since the surface gas pressure changes as the object contracts with time, so if WISE J0808–6443 is significantly younger than 50 Myr the magnetic field strengths will be overestimated and for older ages the magnetic field strengths will be slightly underestimated (G. Feiden, private communication). From these models we derive an age of 59^{+22}_{-26} Myr, which agrees with the 23^{+24}_{-10} Myr found with Baraffe et al. (2015), noting the large error bars which are primarily the result of the uncertainty on T_{eff} . We prefer the Feiden (2016) estimates given these models’ recent success in reproducing observed low-mass isochrones in the young groups Upper Sco (Feiden 2016) and β Pic (Malo et al. 2014b), but both ages are consistent with the 45^{+11}_{-7} Myr isochronal age of Carina (Bell et al. 2015).

5 CONCLUSIONS

The parameters of WISE J0808–6443 determined in this work are summarised in Table 5. Based on all available spectroscopy, photometry and astrometry, we conclude that WISE J0808–6443 is a ~ 45 Myr-old M5 ($\sim 0.1 M_{\odot}$) member of the Carina association at a distance of ~ 90 pc and is actively accreting from a hot circumstellar disc. While rare, the discovery of an accreting low-mass star in the GAYA complex (Carina, Columba, Tuc-Hor) is not unprecedented. Reiners (2009) describe a Li-rich M7.5 star with strong, asymmetric H α emission which they attribute to accretion ($\log \dot{M}_{\text{acc}}/M_{\odot} \approx -10.9$). Their tentative membership assignment to

⁵ $R_{\odot}^N = 695,700 \text{ km}$ = nominal solar radius following IAU 2015 Resolution B3 (Mamajek et al. 2015b).

⁶ The recent IAU 2015 Resolution B2 regarding the IAU bolometric magnitude scale (Mamajek et al. 2015a) suggests an adopted $M_{\text{bol},\odot}$ of 4.74 mag. This differs from the value adopted by Pecaut & Mamajek (2013) by -0.015 mag. To conform with the new resolution and place the luminosity of WISE J0808–6443 on the 2015 IAU scale, we have modified the *J*-band bolometric correction from Pecaut & Mamajek accordingly.

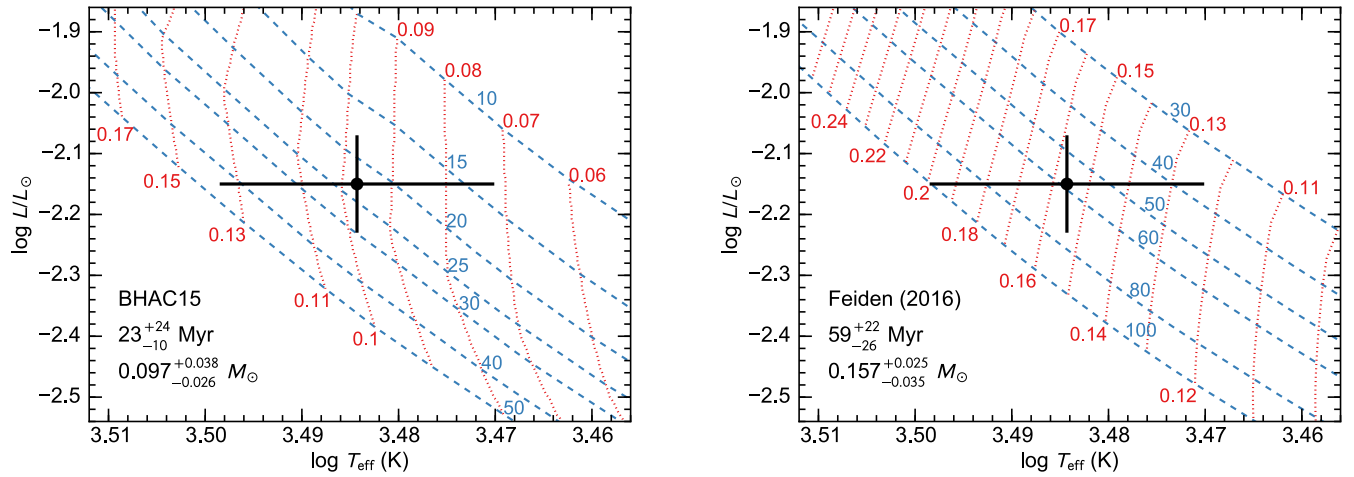


Figure 9. H-R diagram position for WISE J0808–6443, with isochrones and evolutionary tracks for solar metallicity pre-MS stars from Baraffe et al. (2015) (BHAC15, left) and Feiden (2016) (right). The latter incorporate magnetic field strengths appropriate for a 50 Myr star. Interpolating at the position of WISE J0808–6443 we estimate ages of 23^{+24}_{-10} Myr and 59^{+22}_{-26} Myr, respectively, and stellar masses of $0.1^{+0.04}_{-0.03} M_{\odot}$ and $0.16^{+0.03}_{-0.04} M_{\odot}$. Uncertainties are the 68 per cent confidence intervals and were calculated from a Monte Carlo simulation assuming the quoted uncertainties on (linear) T_{eff} and $\log(L/L_{\odot})$.

Table 5. Summary of WISE J080822.18–644357.3 parameters.

Parameter	Value	Units
Right Ascension	122.0924291	$^{\circ}$ (<i>Gaia</i>)
Declination	−64.7325757	$^{\circ}$ (<i>Gaia</i>)
Spectral type	M5	
T_{eff}	3050 ± 100	K
$\mu_{\alpha} \cos \delta$	-12.5 ± 2.1	mas yr $^{-1}$
μ_{δ}	$+29.4 \pm 2.5$	mas yr $^{-1}$
RV	22.7 ± 0.5	km s $^{-1}$
Distance	90 ± 9	pc
EW[Li I]	380 ± 20	mÅ
$\log(L/L_{\odot}^N)$	-2.15 ± 0.08	dex
Radius	0.302 ± 0.036	R_{\odot}^N
Mass ^a	$0.16^{+0.03}_{-0.04}$	M_{\odot}
Age ^b	45^{+11}_{-7}	Myr
(<i>U, V, W</i>)	(−10.3, −23.8, −5.2)	km s $^{-1}$
	$\pm(1.4, 1.1, 1.0)$	
(<i>X, Y, Z</i>)	(12.1, −85.4, −25.8)	pc
	$\pm(4.9, 6.3, 4.2)$	
$T_{\text{disc,hot}}$	1070 ± 100	K
$L_{\text{disc,hot}}$	$0.053 [0..0.11]$	L_{\star}
$T_{\text{disc,warm}}$	230 ± 9	K
$L_{\text{disc,warm}}$	0.067	L_{\star}

^a Mass inferred from HR diagram position, interpolating from the evolutionary tracks of Feiden (2016).

^b Age is from group membership to Carina (Bell et al. 2015), however the isochronal age using the Feiden tracks is consistent with this age (59^{+22}_{-26} Myr; see Fig. 9).

the Tuc-Hor association was confirmed by Gagné et al. (2014). Recently, Boucher et al. (2016) reported finding two brown dwarfs in Columba and Tuc-Hor which host circumstellar discs and show signs of accretion (H α , Pa β emission, respectively). The $0.15 L_{\star}$ fractional disc luminosity of their Tuc-Hor member is similar to the value we find for WISE J0808–6443 and is typical of primordial or early pre-transitional discs.

The fraction of accreting stars in young groups and star-forming regions is observed to fall rapidly with age, with e -folding timescales of 4–5 Myr (e.g. Mamajek 2009; Fedele et al. 2010, with the updated cluster age scale of Bell et al. 2013). The discovery of older accretors like WISE J0808–6443 could be an indication that at least some low-mass stars and brown dwarfs are able to re-

tain their gas reservoirs much longer than previously recognised (Currie et al. 2007; Murphy et al. 2015; Pecaut & Mamajek 2016). Alternatively, some unknown mechanism (tidal disruption of inner gas-giant planets?) may be responsible for generating short-lived, gas-rich discs during the later stages of pre-MS evolution.

The existence of a ~ 45 Myr-old accreting M dwarf expands the parameter space for investigations of planet formation around low-mass stars. The presence of long-lived gas in the disc could contribute multiple important effects to the star’s growing planetary system, such as (1) prolonged accretion of H and He onto the envelopes of growing proto-planets, (2) prolonged gas-drag which could dampen the eccentricities of growing planetesimals and planets, (3) a prolonged epoch of disc torques which may lead to planet migration, or the formation of planets from matter shepherded by moving secular resonances (e.g. Raymond, Barnes & Mandell 2008; Ogiwara & Ida 2009). Finally, the characteristics of the lowest mass pre-MS stars like WISE J0808–6443 and their circumstellar material can also provide important constraints on the conditions that spawn compact systems of small planets in mean-motion resonances orbiting closely around some low-mass stars (e.g. TRAPPIST-1; Gillon et al. 2016).

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